

## Original Research

## Core Ideas

- Unsaturated hydraulic conductivity of stony soils was determined in medium moisture range.
- Evaporation method works for stony soils, even if stone contents are high.
- Theoretical scaling models showed a good agreement with measurements for moderate stone contents.
- Model results and measurements differ markedly for soils with high stone contents.

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# Influence of Stone Content on Soil Hydraulic Properties: Experimental Investigation and Test of Existing Model Concepts

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Studying the role of gravel, stones, or rock fragments on effective soil hydraulic properties (SHPs) is crucial for understanding and predicting soil water processes such as evaporation, redistribution, and water and solute transport through soils containing significant amounts of coarse inclusions. We conducted a laboratory study in which we investigated the effect of stones on the water retention and unsaturated hydraulic conductivity curves of soil–stone mixtures. Stony soils were created by packing predefined masses of soil particles (sand and sandy loam) with diameters <2 mm and crushed basalt (2–5 and 7–15 mm). The resulting mixtures ranged from 0 to 40% (v/v) stone content. The SHPs were determined with the simplified evaporation method. The measurements yielded plausible water retention and hydraulic conductivity curves across a wide moisture range. Results qualitatively showed the expected dependencies of SHPs on volumetric stone content, characterized by a reduction of soil water content and hydraulic conductivity across the whole pressure head range. Measured data suggested that coarse inclusions in soil tend to widen the effective pore-size distribution. Prediction of SHPs of the stony soils, performed by fitting a flexible SHP model to the data of the background soil and scaling it with approaches from the literature, worked well for low stone contents. However, for volumetric stone contents of 25 and 40%, measured SHPs differed substantially from the properties predicted by simple scaling models.

Abbreviations: HCC, hydraulic conductivity curve; PDI, Peters–Durner–Iden; PSD, pore-size distribution; SEM, simplified evaporation method; SHPs, soil hydraulic properties; WRC, water retention curve.

Soils containing stones, gravel, cobbles, or rock fragments are widespread, in particular in mountainous areas, floodplains, and landscapes that have formed on Pleistocene sediments (Meinsen et al., 2014). Here we use the term *stony soils* for soil substrates comprised of a mixture of a background soil (i.e., particles with an effective diameter <2 mm) and larger particles. For convenience, we use the expression *stones* to address the whole variety of larger particles, i.e., gravel, cobbles, stones, or rock fragments. Finally, we use the term *soil* for the background soil where possible.

Stones as structural components impose spatial heterogeneity and alter the soil porosity, the effective pore-size distribution (PSD), pore tortuosity and connectivity, and thus effective soil hydraulic properties (SHPs) of soils. Here we follow the convention of defining SHPs in the framework of continuum theory, where the macroscopically averaged properties, namely volumetric water content, matric potential, and effective hydraulic conductivity, are defined for a representative elementary volume (Bear, 2018). Variably saturated water flow in soils is most commonly modeled with the Richards equation (Richards, 1931), for which SHPs are a mandatory model input. In the following, we use SHPs to summarize the two constitutive relationships (i) soil water retention curve (WRC) and (ii) soil hydraulic conductivity curve (HCC).

Knowledge of the role of coarse inclusions on SHPs is crucial for modeling the hydraulic behavior and solute transport in stony soils and therefore also relevant for land-surface modeling. Stones that are embedded in the soil or on the surface can change the soil infiltration rate (Brakensiek and Rawls, 1994), surface runoff (Sauer and Logsdon, 2002; Poesen and Lavee, 1994), or evaporation (Beckers et al., 2016). However, the findings about

the role of stones on effective SHPs are contradictory. Poesen and Lavee (1994) reported an increase in infiltration and preferential flow as a result of lacunar pores (macropores at the stone–soil interface), while Cousin et al. (2003) reported that neglecting stones in soil leads to an overestimation of percolation to groundwater.

One reason for diverging perceptions on the role of stones in soils could be that experimental observations are sparse. This is related to the fact that determination of the SHPs of stony soils is an experimental challenge, in particular if the stone content is high, and the applicability and reliability of standard measuring techniques is problematic (Verbist et al., 2010, 2013). Key problems, to name a few, are the high effort to obtain and prepare undisturbed samples (Ponder and Alley, 1997; Beckers et al., 2016), the required large sample volume that is needed to obtain a representative elementary volume (Germer and Braun, 2015), the difficulty of placing sensors for monitoring state variables like water content or capillary pressure in such samples (Coppola et al., 2013), and the high local variability of instrumental readings (Corwin and Lesch, 2005). Therefore, SHPs are commonly determined in laboratory experiments for the sieved soil, and the effect of stones on the effective SHPs is taken into account by models that scale the hydraulic properties of the background soil depending on the volumetric or gravimetric stone content.

In general, the effect of stones on SHPs will depend on the stone content, shape, type, orientation, surface roughness, porosity, position, and size, and this is particularly the case for high stone contents (Zimmerman and Bodvarsson, 1995; Verbist et al., 2009; Ma et al., 2010; Tanino and Blunt, 2012; Hlaváčiková et al., 2016). The simplest model concept is to assume that stones represent just a hydraulically inactive volume fraction that does not alter the local physical properties of the soil and only reduces the water content and hydraulic conductivity of the soil linearly by reducing the (effective) flow cross-section. We note that whereas this approach is straightforward for water retention, it is not necessarily valid for hydraulic conductivity due to the effect of stony obstacles on the tortuosity of the water flow paths and local hydraulic gradients. Validating model concepts for these effects is demanding. First, it requires sieving the stony soil and thus involves sample disturbance. Second, the role of porous interfaces between soil matrix and stones, or the role of the orientation of non-spherical stones, cannot be easily accounted for.

Therefore, more complex model concepts have been proposed. Bouwer and Rice (1984) proposed estimating the WRC of stony soil based on the WRC of the background soil and the volumetric stone content. This correction has been discussed as limited in the dry range (Khaleel and Relyea, 1997) and wet range (Ravina and Magier, 1984) of the WRC. Similarly, Hlaváčiková and Novák (2014) proposed a correction of the van Genuchten–Mualem model to obtain the HCC of the stony soils. By studying clay soils containing coarse fragments that were assumed to have zero porosity, Ravina and Magier (1984) showed that the effect of coarse inclusions on the water retention of aggregated clay soils is not accounted for by simply correcting for the reduction in soil porosity, at least not in the high moisture content range. Recently, Parajuli et al. (2017) conducted experiments and numerical

simulations to identify the effective WRC of soils with porous stony inclusions. They showed that neglecting the porosity of stones may lead to a considerable underestimation of water retention and proposed a mixing model that includes the WRC of porous stones. Moreover, stones alter the configuration of pores in the background soil. Fiès et al. (2002) used glass fragments to study the effect of coarse inclusions on soil pore space and water retention. They reported that shrinkage may induce the occurrence of lacunar pores for soil containing more than 25 to 30% clay and stated that in a suction (absolute value of pressure head) range where lacunar pores are filled with water, both lacunar pores and soil pores are engaged in the water retention. In contrast, at higher suctions where the lacunar pores are air filled, only the soil pores contribute to water retention. Overall, this leads to a bimodal effective PSD of the stony soil.

Recent advancements in measurement technology and numerical modeling capabilities have stimulated a new interest in determining the effective SHPs of stony soils (Baetens et al., 2009; Ma et al., 2010; Coppola et al., 2013). Baetens et al. (2009) used inverse modeling of tension infiltrometer data measured in the field along with sand box and pressure chamber data to obtain the WRC of undisturbed stony soils consisting of loam and loamy sand. They compared the results with the WRC of disturbed samples of the soil (<2-mm sieved) obtained from each site considering the correct in situ bulk density. Inverse modeling was applied to assess the influence of stones on the effective SHPs. While a strong influence of stoniness on the WRC was found at low suctions, a minor effect for suctions greater than  $\approx 30$  kPa was reported. However, they reported severe measurement problems at one of their sites where stoniness was high (volumetric stone content  $\approx 70\%$ ) and stated the need for measurements at higher suctions to obtain a quantitative relationship between the volumetric stone content and WRC.

Although several investigations have been conducted to characterize the hydraulic properties of stony soils, they have focused mainly on the WRC and saturated hydraulic conductivity, but hardly at all on the unsaturated hydraulic conductivity. An exception is a recent study by Beckers et al. (2016), who characterized the hydraulic properties of clay soil mixed with glass beads and granite inclusions with a diameter of 10 to 20 mm. Their results showed a decrease in the unsaturated hydraulic conductivity of the mixtures compared with the background soil. They stated measurement difficulties when the volumetric stone content exceeded 20% and concluded that further evaporation experiments using coarser soil textures, higher stone contents ( $>20\%$ ), and different stone characteristics need to be conducted. Therefore, there is a need to measure and describe the WRC and HCC of stony soils across a wide range of suctions. Moreover, there is a lack of data on SHPs and the hydraulic behavior of highly stony soils, i.e., soils with volumetric stone contents exceeding 50%, due to measurement difficulties. Specifically, the installation of the soil moisture and water potential sensors is challenging in these soils. Indeed, tests of measurement devices and methods that can be used to reliably determine the hydraulic properties of highly stony soils are still missing.

The aim of this work was to measure the effect of stone content and size on the effective hydraulic properties of stony soils. This includes explicit measurement of the unsaturated hydraulic conductivity function, which is an innovative aspect of this work. Since measurement of unsaturated conductivity is still rarely performed for soils, and furthermore cannot be done with one single technique across a wide moisture range (Durner and Lipsius, 2006), we were specifically interested in testing the applicability of the simplified evaporation method (SEM; Schindler, 1980) as a measurement technology and method to determine the effective SHPs of stony soils. Besides testing the methodology itself, we wanted to extend the analysis to soil–stone mixtures with very high stone contents and extend the determination of SHPs to drier conditions. For soils free of stones, the SEM is known to give unbiased results for the WRC in the moisture range from full saturation to a suction of  $\approx 100$  kPa and for the HCC in the suction range from 10 to 100 kPa (Peters et al., 2015). However, for stony soils, measurements for such a wide range of suction are so far missing. An additional objective was to use the measured data for evaluating the accuracy of available models that quantify the effect of stones on SHPs.

## Materials and Methods

### Material Properties

Mixtures of two soil materials ( $d < 2$  mm) and two sizes of crushed basalt were prepared in the laboratory. The volumetric stone content in the mixtures,  $R_v$  (dimensionless), was varied in four steps from 0 to 40% and mixtures of two different sizes of stones, 2 to 5 and 7 to 15 mm, with two different soil materials, sandy loam and sand, were investigated. Some basic properties of the materials are listed in Table 1. For a simple nomenclature, we refer to the two size classes of stones as “fine stones” and “medium stones.” We assumed zero porosity for the basalt. This is in agreement with a porosity of 0.4% (v/v) reported by Poesen and Lavee (1994). The soil materials were taken from two sites near Braunschweig, Lower Saxony, Germany. The sand was sampled from the floodplain Schunteraue located 3 km northeast of the city of Braunschweig. The sandy loam was collected at an agricultural site of the Julius-Kühn-Institute in Braunschweig-Völkenrode. The material was sampled at both sites from the topsoil at a depth of 0 to 20 cm, air dried, cleaned of fine roots, and sieved through a 2-mm sieve.

### Sample Preparation

Samples were packed into 5-cm-high stainless steel cylinders with an inner diameter of 8 cm and a volume of  $250 \text{ cm}^3$ . The

gravimetric stone contents of the mixtures (dry mass of stone per total dry mass) were  $R_m = 0, 20, 40$ , and 60%. Combinations of the sand and the sandy loam as embedding materials and the fine and medium stones as embedded materials led to four different types of mixtures. To obtain the targeted gravimetric stone contents,  $R_m$ , predefined proportions of air-dried soil with known water content and dry stones were mixed and added in three portions to the cylinder. While mixing, the material was slightly moistened by spraying with water. This method yielded a quite homogenous distribution of stones in the background soil. Following Yu et al. (1997), the samples were compacted after each addition of materials by raising a weight (mass: 1 kg; contact area:  $50 \text{ cm}^2$ ) seven times to a height of 40 cm and allowing it to fall freely and compact the mixture. The mass of the soil material in the mixtures was calculated with the aim of achieving identical bulk densities of the background soil for the target stone contents, with the reference value taken from compaction of the soil without stones. However, for high stone contents, we were not able to compact the soil in the voids between the stones to the target value, and the respective bulk density of the soil was lower.

Two vertical metal pins were placed in each sample during packing to enable the installation of mini-tensiometers (shaft diameter: 5 mm; tip length: 6 mm) for the evaporation experiment. The pins reached from the base of the samples to the intended height for measuring the pressure head,  $h(t)$  (cm). The falling weight had closely fitting voids at the positions of the metal pins such that it did not hit them but compacted the entire sample surface around them. All mixtures were packed in triplicates. This setup resulted in 48 samples (four mixtures, four stone contents, and three replicates), which were analyzed by the evaporation method (see below). After packing, the samples were saturated with degassed tap water under vacuum for 15 min. The packing, saturation, and subsequent experiments were performed in a temperature-controlled laboratory at  $20 \pm 1^\circ\text{C}$ .

### Determination of Soil Hydraulic Properties Using the Evaporation Method

Evaporation experiments were conducted on the packed samples to determine their WRC and HCC. We used the HYPROP device (Meter Group, Munich) for performing the evaporation experiments. After the packed soil samples were saturated with water, they were set upside down, the metal pins removed, and the HYPROP device mounted by inserting the tensiometers into the respective holes. The whole setup was then turned back again, and the sample surface was exposed to the atmosphere to evaporate.

Table 1. Basic properties of the materials used in experiments.

Material	Origin	Land use	Grain sizes (sand/silt/clay)	Solid density	Organic C
			%	$\text{kg m}^{-3}$	$\text{g kg}^{-1}$
Sand	Schunteraue	floodplain	98/2/0	2650	2.0
Sandy loam	Julius-Kühn-Inst.	agricultural field	63/29/8	2650	7.0
Medium stones	crushed basalt gravel		7–15 mm	2930	0.0
Fine stones	crushed basalt gravel		2–5 mm	2930	0.0



The tensiometers of the HYPROP device measure the pressure head at depths of 1.25 and 3.75 cm at a temporal resolution of 10 min. While the pressure head was recorded automatically, masses of the samples were determined twice per day by weighing on a balance with a resolution of 0.01 g. The point data of soil mass were then interpolated with a cubic Hermite spline to obtain a continuous time series. Peters and Durner (2008a) and Peters et al. (2015) have verified that the error caused by this methodology is negligible for the determination of SHPs on small soil cores. The evaporation experiments were stopped when the lower tensiometer reached its measuring limit of approximately  $h = -2000$  cm. The samples were then dried in an oven at a temperature of  $105^\circ\text{C}$  for at least 24 h until their masses were constant to verify the total dry mass of the mixtures and their components.

The SEM data evaluation was done as described by Peters and Durner (2008a) and Peters et al. (2015). In brief, point data of the WRC were obtained by assigning the sample-averaged water content to the mean of the two tensions measured by the tensiometers. The HCC was calculated by the Darcy–Buckingham law and the assumption that the flux density across the middle height of the soil cylinder equals 50% of the evaporation rate. Peters and Durner (2008a) showed that this method leads to unbiased estimates of the SHPs for a broad range of textures and experimental conditions. The calculations in this study were done using the equations given in Peters et al. (2015), which are implemented in the HYPROP-FIT software (Pertassek et al., 2015).

## Determination of Bulk Density, Porosity, and Volumetric Stone Content

After the evaporation measurements, oven-dried samples were sieved (2-mm mesh size), and the masses of stones,  $m_{\text{st}}$  (g), and soil,  $m_{\text{soil}}$  (g), were determined separately with an accuracy of 0.1 g. The volume of stones,  $V_{\text{st}}$  ( $\text{cm}^3$ ), was calculated from the density of the basalt ( $\rho_{\text{st}} = 2930 \text{ kg m}^{-3}$ ), which was determined by the water displacement method (three replicates) (Webb, 2001). The volume of the soil particles,  $V_{\text{sp}}$  ( $\text{cm}^3$ ), was calculated from the particle density of quartz ( $2650 \text{ kg m}^{-3}$ ). Total dry bulk density,  $\rho_b$  ( $\text{kg m}^{-3}$ ), was calculated as the total dry mass (soil plus stones) divided by the total volume of the sample,  $V_t$  ( $\text{cm}^3$ ). The effective porosity of the stony soil mixture,  $\phi_e$  (dimensionless), was calculated as

$$\phi_e = \frac{V_t - V_{\text{st}} - V_{\text{sp}}}{V_t} \quad [1]$$

and the volumetric stone content as

$$R_v = R_m \frac{\rho_b}{\rho_{\text{st}}} \quad [2]$$

## Modeling the Effect of Stones on Soil Hydraulic Properties

### Parameterization of Soil Water Retention Curves

The WRC was parametrized with the Peters–Durner–Iden (PDI) model as described by Peters (2013), Iden and Durner (2014),

and Peters (2014). This model ensures a water content of zero at oven dryness and is therefore physically more correct than models that consider a residual water content. The equation for the WRC is

$$\theta(h) = (\theta_s - \theta_r) S_c(h) + \theta_r S_{\text{nc}}(h) \quad [3]$$

where  $\theta_s$  ( $\text{cm}^3 \text{ cm}^{-3}$ ) is the saturated water content,  $\theta_r$  ( $\text{cm}^3 \text{ cm}^{-3}$ ) is the maximum non-capillary water content,  $S_c(h)$  (dimensionless) is the capillary saturation function, and  $S_{\text{nc}}(h)$  (dimensionless) is the non-capillary saturation function for water stored in water films on grain surfaces and in incompletely filled capillaries. The capillary saturation function is defined as

$$S_c(h) = \frac{\Gamma(h) - \Gamma_0}{1 - \Gamma_0} \quad [4]$$

where  $\Gamma(h)$  is a basic saturation function,  $\Gamma_0 = \Gamma(h_0)$ , and  $h_0$  is the pressure head corresponding to the oven dryness, which is set to  $h_0 = -10^{6.8}$  cm throughout this work. In this study, we used the equation proposed by Fredlund and Xing (1994) (FX) for  $\Gamma(h)$ :

$$\Gamma(h) = \left\{ \ln \left[ e + (-\alpha h)^n \right] \right\}^{-m} \quad [5]$$

with the shape parameters  $\alpha$  ( $\text{cm}^{-1}$ ),  $n$  (dimensionless), and  $m$  (dimensionless). The saturation function for non-capillary water is

$$S_{\text{nc}}(h) = 1 + \frac{1}{x_a + x_0} \left\{ x - x_a + \ln \left[ 1 + \exp \left( \frac{x_a - x}{b} \right) \right] \right\} \quad [6]$$

where  $x = \log_{10}(-h)$ ,  $x_a = \log_{10}(h_a)$ ,  $x_0 = \log_{10}(-h_0)$ , and  $h_a = \alpha^{-1}$ . The parameter  $b$  (dimensionless) smooths  $S_{\text{nc}}(h)$  around  $h_a$  and ensures a continuous soil water capacity function. Empirical expressions for  $b$  can be found in Iden and Durner (2014). The WRC is fully defined by five parameters:  $\theta_r$ ,  $\theta_s$ ,  $\alpha$ ,  $n$ , and  $m$ . The FX-PDI model was selected among the 16 functions provided by the HYPROP-FIT software because it yielded a sound functional description across the whole moisture range with the smallest discrepancy between the model and observed data.

## Parameterization of Soil Hydraulic Conductivity Curves

The HCC of all samples, i.e., background soil and stony soils, were parametrized with the FX-PDI model. Hydraulic conductivity as a function of pressure head was calculated as the sum of the hydraulic conductivities of fully saturated pores and the hydraulic conductivity of partially saturated pores (Peters, 2013):

$$K(h) = K_{\text{sc}} K_{\text{rc}}(h) + K_{\text{snc}} K_{\text{rnc}}(h) \quad [7]$$

where  $K_{\text{sc}}$  ( $\text{cm d}^{-1}$ ) is the saturated hydraulic conductivity concerning capillary flow,  $K_{\text{rc}}$  (dimensionless) is the relative capillary conductivity function, and  $K_{\text{snc}}$  ( $\text{cm d}^{-1}$ ) and  $K_{\text{rnc}}$  (dimensionless) are the saturated and relative hydraulic conductivities reflecting non-capillary (film and corner) flow.

The relative hydraulic conductivity function  $K_{\text{rc}}$  is calculated by Mualem's capillary bundle model (Mualem, 1976), which is applied to the water stored in fully saturated capillaries only

(Peters, 2013). Mualem's model for the capillary saturation function defined by Eq. [4] is (Peters, 2014)

$$K_{rc}(h) = S_c^\tau \left( \frac{\int_{\Gamma_0}^{\Gamma} b^{-1} d\Gamma^*}{\int_{\Gamma_0}^1 b^{-1} d\Gamma^*} \right)^2 \quad [8]$$

where  $\tau$  (dimensionless) is a tortuosity parameter introduced by Mualem (1976), and  $\Gamma^*$  is a dummy variable for integration. Because no closed-form solution of the integrals in Eq. [8] is known for the FX saturation function, the function  $K_{rc}(h)$  was computed by a numerical integration.

The relative hydraulic conductivity function for flow in films and incompletely filled capillaries is calculated by (Peters, 2013)

$$K_{rnc}(S_{nc}) = \left( \frac{h_0}{h_a} \right)^{c(1-S_{nc})} \quad [9]$$

where  $c$  (dimensionless) is a film-flow parameter set to  $-1.5$ , as suggested by Tokunaga (2009) for ideally and closely packed monodisperse spheres. If the soil WRC is known and the parameter  $c$  is set to  $-1.5$ , the remaining free parameters to compute  $K(h)$  are the capillary and non-capillary saturated conductivities  $K_{sc}$  and  $K_{snc}$  and Mualem's tortuosity parameter  $\tau$ .

### Parameter Estimation for Background Soil

We fitted the FX-PDI model to the point data of the SHPs of the sand and sandy loam. Curve fitting was performed using the HYPROP-FIT software (Pertassek et al., 2015), which minimizes a nonlinear least-squares objective function using the shuffled complex evolution algorithm (SCE-UA) of Duan et al. (1992). Details of the fitting algorithm were given by Peters et al. (2015). The resulting WRC and HCC for the soils are denoted by  $\hat{\theta}_{soil}(h)$  and  $\hat{K}_{soil}(h)$ , respectively.

### Prediction of the Effect of Stone Content on Water Retention Curves

The effective WRC of stony soil,  $\theta_e(h)$ , was predicted from the WRC of the soil,  $\hat{\theta}_{soil}(h)$ , and the volumetric stone contents,  $R_v$ , using the model of Bouwer and Rice (1984) and Flint and Childs (1984):

$$\theta_e(h) = (1 - R_v) \hat{\theta}_{soil}(h) \quad [10]$$

where  $(1 - R_v)$  is the volumetric content of the background soil. This model is built on the simple assumption that water stored in the stones is zero and only the soil contributes to the WRC of the stony soil. Furthermore, it is assumed that bulk density, porosity, and the PSD of the soil remain unaffected by mixing with the coarse inclusions and are therefore all independent of  $R_v$ . We scaled the WRC of the soil material parameterized with the FX-PDI model by Eq. [3] and compared the resulting WRC,  $\theta_e(h)$ , with the measured point data of the WRC obtained from the SEM. The mismatch was quantified by the root mean squared deviation (RMSD) of the water contents.

### Prediction of the Effect of Stone Content on Soil Hydraulic Conductivity Curves

Several models have been proposed for calculating the dependence of the effective saturated hydraulic conductivity of stony soil,  $K_{sc}$  ( $\text{cm d}^{-1}$ ), on stone content. Most models relate the proportion of the hydraulic conductivities of the stony soil and the background soil to the volumetric or gravimetric stone content. The relative saturated hydraulic conductivity,  $K_{rst}$  (dimensionless), of stony soil is defined as

$$K_{rst} = \frac{K_{sc}}{K_{soil}} \quad [11]$$

where  $K_{soil}$  ( $\text{cm d}^{-1}$ ) is the saturated hydraulic conductivity of the soil. Peck and Watson (1979) derived an equation for  $K_{rst}$  based on Maxwell's model (Zimmerman and Bodvarsson, 1995). By assuming that stones are impermeable and do not interact with each other, they proposed:

$$K_{rst} = \frac{2(1 - R_v)}{2 + R_v} \quad [12]$$

for spherically shaped stones, and

$$K_{rst} = \frac{1 - R_v}{1 + R_v} \quad [13]$$

for cylindrically shaped stones. Both equations have been derived from heat-transfer theory.

Bouwer and Rice (1984) proposed to calculate  $K_{rst}$  from the void ratio of the stony soil ( $e_c$ ) divided by the void ratio of the background soil ( $e_{soil}$ ):

$$K_{rst} = \frac{e_c}{e_{soil}} \quad [14]$$

Assuming that the stones have zero porosity, this equation simplifies to

$$K_{rst} = \frac{V_{sp}}{V_{sp} + V_{st}} \quad [15]$$

Ravina and Magier (1984) proposed the equation

$$K_{rst} = 1 - R_v \quad [16]$$

Other models that have not been applied in this study were presented by Brakensiek et al. (1986) and by Novák et al. (2011), who presented an empirical modification of Eq. [16] that was derived from numerical simulations with the Richards equation assuming a stone size of 10 cm. Figure 1 (left) illustrates  $K_{rst}$  as a function of volumetric stone content for some of the models presented above. For the porosities of the soil realized in this study (36–51%, see results), the Bouwer and Rice model is very similar to the Maxwell model for spheres and cylinders. If the soil has a porosity significantly greater than 50%, the Bouwer and Rice model predicts a stronger reduction of hydraulic conductivity than the Maxwell model assuming cylindrical inclusions (not shown). However, we note that the differences in the models for the reduction of soil hydraulic conductivity

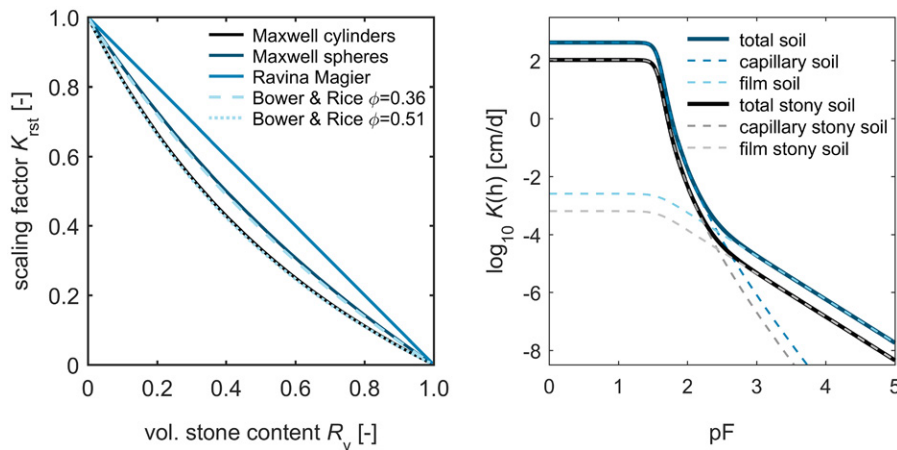


Fig. 1. Model concept for the effect of stones on the hydraulic conductivity curve. Left: comparison of the four models for scaling the saturated hydraulic conductivity as a function of stone content used in this study. The model of Bouwer and Rice is shown for two different porosities of the soil,  $\phi$ , which mark the range of values found in this study. The porosity of the soil must not be mistaken with the porosity of the stony soil,  $\phi_e$ , defined by Eq. [1]. Right: scaling of the hydraulic conductivity curve, exemplified by the Maxwell model with a volumetric stone content of 50%. The hydraulic conductivity curve is the result of the superposition of the capillary and film flow curves, which are both scaled by the Maxwell model.

by the presence of stones are minor compared with other sources of variability and uncertainty in practical situations, and even to measurement uncertainty.

The effective HCC of the stony soil,  $K_e(h)$ , was modeled by scaling the unsaturated hydraulic conductivity curve of the soil,  $\hat{K}_{soil}(h)$ , with the reduction factor  $K_{rst}$ :

$$K_e(h) = K_{rst} \hat{K}_{soil}(h) \quad [17]$$

This simple concept is identical to the one presented by Hlaváčiková and Novák (2014), who proposed a correction of the van Genuchten–Mualem model (van Genuchten, 1980) for stony soils. The model concept is illustrated in Fig. 1 (right), where hydraulic conductivities (capillary, non-capillary, and total) are shown as a function of  $pF$ . The soil  $pF$  is defined as  $pF = \log_{10}(|h|)$ , where  $h$  is the pressure head in units of centimeters (Schofield, 1935). Figure 1 shows that the capillary and non-capillary hydraulic conductivities are both scaled by the same factor  $K_{rst}$ . The mismatch between the modeled and observed  $K(h)$  data was quantified by the RMSD, calculated for the common logarithm of  $K(h)$ .

## Results and Discussion

### Bulk Densities and Stone Contents

Dry masses of the soil and stones in the samples, gravimetric and volumetric stone contents, bulk densities of the soil, and porosities of the mixtures are presented in Table 2. Gravimetric stone contents,  $R_m$ , in our packed samples were very close to the targeted values (0, 20, 40, and 60%), and the resulting volumetric stone contents vary from 0 to almost 40%, a range of stone contents that has hardly been studied before. The bulk density of the soil was rather high due to the applied compaction technique. Overall, soil bulk densities decreased with increasing stone content. For the sandy loam, similar bulk densities were achieved for the low and medium stone contents, but the bulk density decreased markedly for the highest stone content. The reduction in bulk densities of the sand occurred at lower stone contents. These trends were independent of the stone size. Possibly, the presence of stones protects parts of the soil in the voids between stones against the compaction force of the packing process.

For field soils, it has been reported that a higher stone content leads to a lower bulk density of the background soil (Poesen and Lavee, 1994; Fiès et al., 2002). According to Poesen and Lavee (1994), this is caused by the following processes. First, the presence of stones (larger inclusions) in soil even in low amounts restricts the contact of soil particles and implies a looser packing of them. Second, stone and soil have different shrink–swell or freeze–thaw characteristics. As a result, natural soils commonly have extra cracks and macropores at the interfaces of stones and soil. During the packing process, when the stone content exceeds a threshold, stones come in a direct contact with each other and protect the space between them from the load of the overburden material or the compaction force. We assume that the latter cause was dominant in our experiments: the compaction force was no longer protruding fully into the mixture.

### Water Retention Curves

Figure 2 illustrates the effective water retention data from the SEM measurements, the fitted

Table 2. Basic physical characteristics of the soil–stone mixtures

Soil or stone size	Gravimetric stone content	Stone dry mass	Soil dry mass	Volumetric stone content	Soil particle content	Mixture porosity	Soil bulk density
mm	g g <sup>-1</sup>	g	g	L L <sup>-1</sup>	L L <sup>-1</sup>		kg L <sup>-1</sup>
Sandy loam	0	0	403.6	0	0.61	0.39	1.62
2–5	0.20	89.4	355.4	0.12	0.54	0.34	1.63
	0.39	188.8	291.9	0.26	0.44	0.30	1.58
	0.59	282.4	199.0	0.39	0.30	0.31	1.30
7–15	0.20	87.8	341.6	0.12	0.52	0.36	1.57
	0.40	195.5	289.5	0.27	0.44	0.29	1.59
	0.60	290.4	190.6	0.41	0.30	0.29	1.34
Sand	0	0	424.8	0	0.64	0.36	1.69
2–5	0.20	90.9	364.6	0.12	0.54	0.34	1.63
	0.40	195.1	297.8	0.26	0.43	0.31	1.55
	0.59	299.1	209.5	0.40	0.31	0.29	1.37
7–15	0.20	89.7	353.3	0.12	0.51	0.37	1.54
	0.40	187.5	281.4	0.25	0.42	0.32	1.50
	0.60	299.2	198.9	0.41	0.30	0.29	1.34



FX-PDI model to the background soil, and the predicted WRCs of stony soils obtained from scaling with Eq. [10] for two background soils and stone sizes. An excellent agreement of the replicate measurements of each variant is visible. This refers in particular to the medium moisture range between about pF 1.8 (–60 cm) and the measurement limit of the SEM around pF 3.0 (–1000 cm) and confirms the reproducibility of our packing method and applied measurement technique to determine the hydraulic properties of the stony soils. Only near saturation replicates show differences in the water contents, which reflects small differences in the volume of coarse pores and might be caused by inevitable variations in the packing process.

For the soil without stones and the mixtures with low stone contents, volumetric water content did not decrease until the distinct air entry was reached. We conclude that lacunar pores did not evolve at the interface between the stones and the background soil. This changed slightly for the medium stone content and was no longer the case for the highest stone content. There, the early decrease of water saturation with increasing suction indicates a significantly wider PSD including macropores.

The scaled WRC obtained from Eq. [10] predicts the observed data very well for the low volumetric stone content (12%). This is confirmed by the RMSD values (<1%, except for sand with 7–15-mm stones) in Table 3. However, the agreement becomes weaker for the medium and high stone contents. For the medium stone content (26%), the prediction is still good in the medium moisture range (pF > 1.8). However, in the wetter range a slight but significant trend

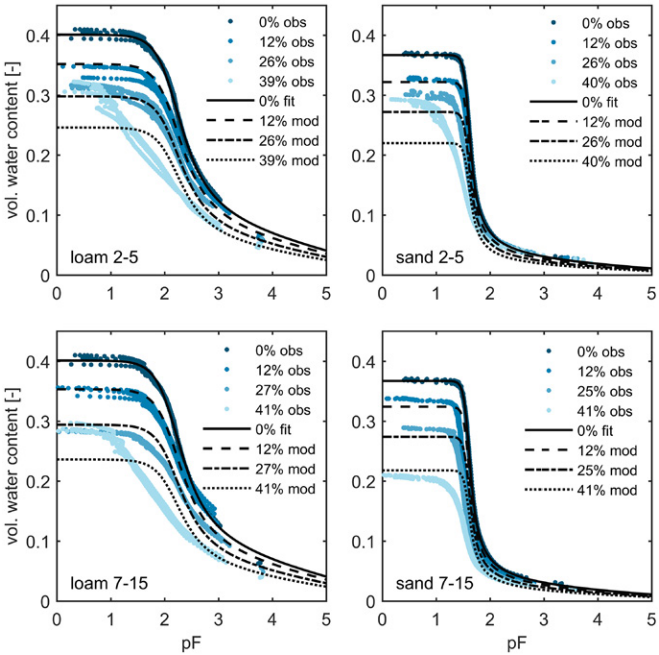


Fig. 2. Measured water retention curves for the sandy loam (left) and the sand (right) with different volumetric stone contents (top: 2–5-mm stone size; bottom: 7–15 mm). Shown are the measured data obtained from the simplified evaporation method (circles), the FX-PDI model fitted to the water retention data of the soils (solid line), and the water retention curves scaled with Eq. [10] for the mixtures (dashed and dotted lines).

of an increasing water content toward saturation becomes evident. This trend cannot be predicted by the simple scaling approach (Eq. [10]) and reflects the formation of additional coarse pores, (up to macropores) across a wide size range. This pore space might be still rather insignificant with respect to the retention properties but can play a big role for the HCC near water saturation despite its small volume (Durner, 1994). Upon closer inspection of the measured WRC data, we see a shift of the air-entry pressures toward smaller suctions. This cannot be predicted by the simple scaling model where the air entry remains unchanged and the presence of stones only reduces the available void space for the soil matrix.

For the highest stone content of 40%, the scaled model no longer matches the data, and systematic discrepancies arise. These comprise (i) a shift in the air-entry value of the measured data to the left (toward larger pores), (ii) an increase in the width of the PSD including a decrease in the slope of the WRC, and (iii) an unexpected decrease in water content near saturation that cannot be described by the scaling (saturated water contents for 40% and 26% stone contents are almost equal). These effects reflect the lower bulk density of the soil in the void space between stones. The increased width of the PSD reflects a greater local heterogeneity of the soil matrix in the void space between the stones, probably including lacunar pores at the interfaces between soil matrix and stone surfaces.

### Hydraulic Conductivity Curves

The effect of stone content on the HCC is illustrated in Fig. 3. Because conductivity values drop across many of orders of magnitudes in drying soils, the curves are shown on log–log

Table 3. Performance of the different scaling models for the stony soils quantified by the RMSD for water content (WRC, 3rd column) and the RMSD for the common logarithm of hydraulic conductivity (Columns 4–7). Minimum values are in *italics*.

Stone size	Volumetric stone content	RMSD				
		Water retention curve Eq. [10]	Maxwell (spheres) Eq. [12]	Maxwell (cylinders) Eq. [13]	Bouwer and Rice Eq. [15]	Ravina and Magier Eq. [16]
mm						
Sandy loam	0.00	0.005	0.077	0.077	0.077	0.077
2–5	0.12	0.010	0.131	0.117	0.127	0.150
	0.26	0.010	0.358	0.332	0.347	0.391
7–15	0.39	0.035	0.586	0.524	0.520	0.660
	0.12	0.012	0.249	0.230	0.242	0.271
	0.27	0.015	0.211	0.205	0.207	0.231
Sand	0.41	0.056	0.382	0.326	0.327	0.454
	0.00	0.003	0.065	0.065	0.065	0.065
	2–5	0.12	0.006	0.128	0.146	0.133
7–15	0.26	0.022	0.465	0.508	0.483	0.418
	0.40	0.042	0.507	0.539	0.535	0.478
	0.12	0.040	0.194	0.214	0.203	0.175
	0.25	0.039	0.216	0.237	0.227	0.201
	0.41	0.043	0.333	0.351	0.351	0.330

plots ( $\log K$  vs.  $pF$ ). A clear feature for all curves of the sandy soil is the typical “bend” in the hydraulic conductivity data, which indicates a transition from capillary-dominated to a film-flow-dominated flow regime. This change in slope requires the use of a model accounting for film flow for the functional description of the data (Peters and Durner, 2008b; Peters, 2013). This effect is not seen for the fine-textured soil.

With respect to the differences in the measured curves due to the presence of stones, we first acknowledge that the reproducibility of the measurements is very good, which allows clear identification of the trends caused by increasing stone contents. In general, the unsaturated hydraulic conductivity of the stony soil at a given matric head decreases with increasing stone content, as described by the simple scaling models. However, the effect appears minor on the logarithmic scale for both measured and predicted curves. For samples with  $R_v \leq 27\%$ , some of the measured data even overlap, in particular for larger stone size. This indicates that measurement uncertainty and variability between replicates exceeds the systematic effect of stones on the hydraulic conductivity.

A comparison of the performance of the different models to scale the HCC shows that the Maxwell model assuming cylindrical inclusions (black line in Fig. 1) had the best performance for the sandy loam–stone mixtures. The ability of the different models to predict the WRC and the HCC of stony soil is summarized in Table 3. As indicated in Fig. 1, the Maxwell model assuming

spheres and the Bouwer and Rice model performed very similarly. For the highest stone content, the models led to a considerable overestimation of the hydraulic conductivity throughout the whole measured range of tensions. This coincides well with the mismatch of the WRC, which was related to a change in the fine-soil PSD as a consequence of the loose packing.

Comparison of the performance of the different models to scale the HCC in Table 3 shows a better performance of the model proposed by Ravina and Magier (1984) in sandy soil for volumetric stone contents  $<40\%$ . This is in agreement with the results reported by Beckers et al. (2016), although their results were obtained for lower stone contents ( $R_v \leq 20\%$ ). Similar to the sandy loam, scaling of the HCC for the sand–stone mixtures worked relatively well for  $R_v$  values up to 26% and failed for the higher stone contents for both large and small stone sizes. However, the RMSD values for all of the applied models show a marked increase for  $R_v > 26\%$ , indicating a fundamental mismatch. This finding is in a close agreement with those of Fiès et al. (2002), who reported a strongly increasing mismatch for a threshold value of 30% stone content.

## Summary and Conclusions

The aim of our study was to measure the effect of stones on the hydraulic properties of two soil textures, i.e., sand and sandy loam soils. Experiments were conducted on disturbed samples consisting of a background soil mixed with different contents of crushed basalt. Evaporation measurements on 250-cm<sup>3</sup> soil cores yielded plausible effective hydraulic properties, as previously shown for soils. The obtained retention data ranged from saturation to about  $pF$  3, and hydraulic conductivity data ranged from  $pF$  2 to  $pF$  3. Even for mixtures with high stone contents ( $R_v \approx 40\%$ ), the results were highly reproducible.

The predicted WRC of stony soils, obtained from scaling the retention curve of the soil with the model of Bouwer and Rice (1984), matched the observations for low stone contents but tended to increasingly diverge from the measurements for higher stone contents. This was most remarkable for the highest stone content with  $R_m \geq 40\%$ . There are two reasons for this. First, the WRC near saturation changed with increasing stone content due to the additional formation of coarse voids at the stone–soil interfaces. Second, a lower bulk density of the soil in the voids between the stones, caused by the inability to pack the samples to the target density, led to wider PSD and a higher local heterogeneity of the pore system for the high stone content. As a consequence, the properties of the mixtures with a high stone content could not be predicted well by the applied scaling models. We note that the models assume the physical properties of the background soil, in particular its pore-size distribution, to be invariant. Given the observed changes in the porosity of the background soil with stone content, a further improvement of the scaling concept would result from consideration of the effect of bulk density on the hydraulic properties of the background soil. Recently, Tian et al. (2018) presented models for predicting the WRCs as a function of bulk density that scale simultaneously the water content and pressure head.

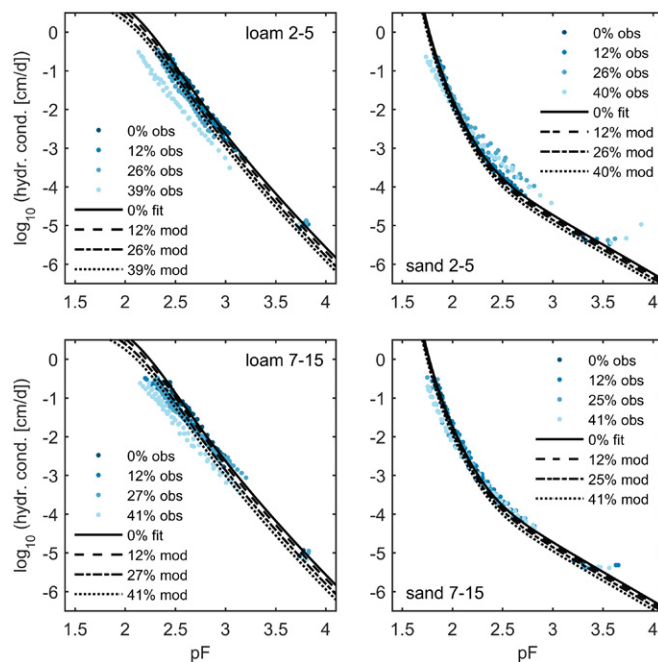


Fig. 3. Measured hydraulic conductivity (hydr. cond.) curves for the sandy loam (left) and the sand (right) with different volumetric stone contents (top: 2–5-mm stone size; bottom: 7–15 mm). Shown are the measured data obtained from the simplified evaporation method (circles), the FX-PDI model fitted to the soil data (solid line), and the predicted hydraulic conductivity curves (dashed and dotted lines). For the sandy loam, the Maxwell model (cylinders, Eq. [13]) performed best and is shown. The model of Ravina and Magier (Eq. [16]) performed best for the sand and is therefore shown in the right plots.



The HCC were successfully determined with the SEM in the pressure head range between pF 1.8 and pF 3. To the best of our knowledge, this is the first time that the conductivity curves in this intermediate moisture range and for very high stone contents have not only been predicted but actually measured. Replicate measurements agreed well, indicating the applicability of the chosen measurement technique. We found the influence of stones on the total hydraulic conductivity to be moderate and, by tendency, in good agreement with the model predictions. This indicates that low and medium amounts of stones that are embedded in a soil lead to a moderate reduction in the effective hydraulic conductivity. The reduction is approximately proportional to the reduction in the cross-sectional area available for flow. However, for high stone contents, the fundamental scaling assumptions (i.e., invariant properties of the soil) broke down and measurements differed substantially from the model predictions.

Up to the present, most studies have focused on the volumetric stone content as the most influential factor in estimating the hydraulic properties of stony soils. However, shape, orientation, size distribution, roughness of the stone surface, stone porosity, and placement may also play important roles in changing the effective SHPs (Hlaváčiková et al., 2016). Although the existing work points in the right direction, our results suggest a need for further experimental investigations as a base for developing models that consider more characteristics of the stones. For instance, when stones with higher effective porosity are embedded in soil, there might be water transfer between soil and stones that would change the WRC of stony soils, in particular in the dry range (Parajuli et al., 2017). Furthermore, the role of porous stones on solute transport in unsaturated soil has not been thoroughly investigated until now and is of great interest for practical problems, such as the movement of fertilizers or pesticides through stony vadose zones toward the groundwater.

A deficit of the presented study is the use of relatively small, packed columns, which limits the stone size and does not fully represent the physical properties of stony field soils. The objective of this study was to validate existing scaling models for the influence of stones on effective SHPs, and such a test is best conducted under well-controlled laboratory conditions. To represent natural soil systems better, larger and undisturbed stony soil samples should be investigated in the future because they include the structural heterogeneity created by stones under field conditions. In principle, any laboratory method to determine SHPs can be applied to stony soils, e.g., multistep outflow (Durner and Iden, 2011), suction table, or pressure plate (Dane and Hopmans, 2002). Evaporation experiments can also be conducted on larger samples, either packed or undisturbed, to ensure more representative systems. However, these experiments must be evaluated by inverse modeling (Romano and Santini, 1999; Weber et al., 2017) because the assumptions of the simplified evaporation method are less valid for the resulting sample heights (Peters and Durner, 2008a). Conducting experiments on undisturbed stony soils poses great challenges because field sampling is difficult and the installation of sensors like tensiometers or time-domain reflectometry probes in stony soils is not trivial (Coppola et al., 2013).

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## References

- Baetens, J.M., K. Verbist, W.M. Cornelis, D. Gabriels, and G. Soto. 2009. On the influence of coarse fragments on soil water retention. *Water Resour. Res.* 45:W07408. doi:10.1029/2008WR007402
- Bear, J. 2018. Modeling phenomena of flow and transport in porous media. Springer, Cham, Switzerland. doi:10.1007/978-3-319-72826-1
- Beckers, E., M. Pichault, W. Pansak, A. Degré, and S. Garré. 2016. Characterization of stony soils' hydraulic conductivity using laboratory and numerical experiments. *Soil* 2:421–431. doi:10.5194/soil-2-421-2016
- Bouwer, H., and R.C. Rice. 1984. Hydraulic properties of stony vadose zones. *Groundwater* 22:696–705. doi:10.1111/j.1745-6584.1984.tb01438.x
- Brakensiek, D.L., and W.J. Rawls. 1994. Soil containing rock fragments: Effects on infiltration. *Catena* 23:99–110. doi:10.1016/0341-8162(94)90056-6
- Brakensiek, D.L., W.J. Rawls, and G.R. Stephenson. 1986. Determining the saturated conductivity of a soil containing rock fragments. *Soil Sci. Soc. Am. J.* 50:834–835. doi:10.2136/sssaj1986.03615995005000030053x
- Coppola, A., G. Dragonetti, A. Comegna, N. Lamaddalena, B. Caushi, M.A. Haikal, and A. Basile. 2013. Measuring and modeling water content in stony soils. *Soil Tillage Res.* 128:9–22. doi:10.1016/j.still.2012.10.006
- Corwin, D.L., and S.M. Lesch. 2005. Apparent soil electrical conductivity measurements in agriculture. *Comput. Electron. Agric.* 46:11–43. doi:10.1016/j.compag.2004.10.005
- Cousin, I., B. Nicoulaud, and C. Coutadeur. 2003. Influence of rock fragments on the water retention and water percolation in a calcareous soil. *Catena* 53:97–114. doi:10.1016/S0341-8162(03)00037-7
- Dane, J.H., and J.W. Hopmans. 2002. Water retention and storage: Laboratory. In: J.H. Dane and G.C. Topp, editors, *Methods of soil analysis. Part 4. Physical methods*. SSSA Book Ser. 5. SSSA, Madison, WI. p. 675–719. doi:10.2136/sssabookser5.4.c25
- Duan, Q., S. Sorooshian, and V. Gupta. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resour. Res.* 28:1015–1031. doi:10.1029/91WR02985
- Durner, W. 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. *Water Resour. Res.* 30:211–223. doi:10.1029/93WR02676
- Durner, W., and S.C. Iden. 2011. Extended multistep outflow method for the accurate determination of soil hydraulic properties near water saturation. *Water Resour. Res.* 47:W08526. doi:10.1029/2011WR010632
- Durner, W., and K. Lipsius. 2006. Determining soil hydraulic properties. In: M.G. Anderson and J.J. McDonnell, editors, *Encyclopedia of hydrological sciences*. John Wiley & Sons, Chichester, UK. p. 1121–1144. doi:10.1002/0470848944.hsa077b
- Fiès, J.C., N.D.E. Louvigny, and A. Chanzy. 2002. The role of stones in soil water retention. *Eur. J. Soil Sci.* 53:95–104. doi:10.1046/j.1365-2389.2002.00431.x
- Flint, A.L., and S.W. Childs. 1984. Physical properties of rock fragments and their effect on available water in skeletal soils. In: J.D. Nichols et al., editors, *Erosion and productivity of soils containing rock fragments*. SSSA Spec. Publ. 13. SSSA, Madison, WI. p. 99–103. doi:10.2136/sssaspecpub13.c10
- Fredlund, D.G., and A. Xing. 1994. Equations for the soil-water characteristic curve. *Can. Geotech. J.* 31:521–532. doi:10.1139/t94-061
- Germer, K., and J. Braun. 2015. Determination of anisotropic saturated hydraulic conductivity of a macroporous slope soil. *Soil Sci. Soc. Am. J.* 79:1528–1536. doi:10.2136/sssaj2015.02.0071
- Hlaváčiková, H., and V. Novák. 2014. A relatively simple scaling method for describing the unsaturated hydraulic functions of stony soils. *J. Plant Nutr. Soil Sci.* 177:560–565. doi:10.1002/jpln.201300524
- Hlaváčiková, H., V. Novák, and J. Šimůnek. 2016. The effects of rock fragment shapes and positions on modeled hydraulic conductivities of stony soils. *Geoderma* 281:39–48. doi:10.1016/j.geoderma.2016.06.034
- Iden, S.C., and W. Durner. 2014. Comment on “Simple consistent models for water retention and hydraulic conductivity in the com-

- plete moisture range" by A. Peters. *Water Resour. Res.* 50:7530–7534. doi:10.1002/2014WR015937
- Khaleel, R., and J.F. Relyea. 1997. Correcting laboratory-measured moisture retention data for gravels. *Water Resour. Res.* 33:1875–1878. doi:10.1029/97WR01068
- Ma, D.H., M.A. Shao, J.B. Zhang, and Q.J. Wang. 2010. Validation of an analytical method for determining soil hydraulic properties of stony soils using experimental data. *Geoderma* 159:262–269. doi:10.1016/j.geoderma.2010.08.001
- Meinsen, J., J. Winsemann, J. Roskosch, C. Brandes, M. Frechen, S. Dultz, and J. Böttcher. 2014. Climate control on the evolution of Late Pleistocene alluvial-fan and aeolian sand-sheet systems in NW Germany. *Boreas* 43:42–66. doi:10.1111/bor.12021
- Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* 12:513–522. doi:10.1029/WR012i003p00513
- Novák, V., K. Křápa, and J. Šimůnek. 2011. Determining the influence of stones on hydraulic conductivity of saturated soils using numerical method. *Geoderma* 161:177–181. doi:10.1016/j.geoderma.2010.12.016
- Parajuli, K., M. Sadeghi, and S.B. Jones. 2017. A binary mixing model for characterizing stony-soil water retention. *Agric. For. Meteorol.* 244–245:1–8. doi:10.1016/j.agrformet.2017.05.013
- Peck, A.J., and J.D. Watson. 1979. Hydraulic conductivity and flow in non-uniform soil. In: *Workshop on Soil Physics and Field Heterogeneity*. 12–14 Feb. 1979. CSIRO Div. of Environ. Mech., Canberra, Australia.
- Pertassek, T., A. Peters, and W. Durner. 2015. HYPROP-FIT software user's manual, V.3.0. UMS GmbH, Munich, Germany.
- Peters, A. 2013. Simple consistent models for water retention and hydraulic conductivity in the complete moisture range. *Water Resour. Res.* 49:6765–6780. doi:10.1002/wrcr.20548
- Peters, A. 2014. Reply to comment by S. Iden and W. Durner on "Simple consistent models for water retention and hydraulic conductivity in the complete moisture range". *Water Resour. Res.* 50:7535–7539. doi:10.1002/2014WR016107
- Peters, A., and W. Durner. 2008a. Simplified evaporation method for determining soil hydraulic properties. *J. Hydrol.* 356:147–162. doi:10.1016/j.jhydrol.2008.04.016
- Peters, A., and W. Durner. 2008b. A simple model for describing hydraulic conductivity in unsaturated porous media accounting for film and capillary flow. *Water Resour. Res.* 44:W11417. doi:10.1029/2008WR007136
- Peters, A., S.C. Iden, and W. Durner. 2015. Revisiting the simplified evaporation method: Identification of hydraulic functions considering vapor, film and corner flow. *J. Hydrol.* 527:531–542. doi:10.1016/j.jhydrol.2015.05.020
- Poesen, I., and H. Lavee. 1994. Rock fragments in top soils: Significance and processes. *Catena* 23:1–28. doi:10.1016/0341-8162(94)90050-7
- Ponder, F., Jr., and D.E. Alley. 1997. Soil sampler for rocky soils. Res. Note NC-371. US For. Serv., North Central For. Exp. Stn., St. Paul, MN. doi:10.2737/NC-RN-371
- Ravina, I., and J. Magier. 1984. Hydraulic conductivity and water retention of clay soils containing coarse fragments. *Soil Sci. Soc. Am. J.* 48:736–740. doi:10.2136/sssaj1984.03615995004800040008x
- Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. *Physics* 1:318–333. doi:10.1063/1.1745010
- Romano, N., and A. Santini. 1999. Determining soil hydraulic functions from evaporation experiments by a parameter estimation approach: Experimental verifications and numerical studies. *Water Resour. Res.* 35:3343–3359. doi:10.1029/1999WR900155
- Sauer, T.J., and S.D. Logsdon. 2002. Hydraulic and physical properties of stony soils in a small watershed. *Soil Sci. Soc. Am. J.* 66:1947–1956. doi:10.2136/sssaj2002.1947
- Schindler, U. 1980. Ein Schnellverfahren zur Messung der Wasserleitfähigkeit im teilgesättigten Boden an Stechzylinderproben. *Arch. Acker- Pflanzenbau Bodenk.* 24:1–7.
- Schofield, R.K. 1935. The pF of water in soil. In: E.M. Crowther et al., editors, *Transactions of the 3rd International Congress on Soil Science*, Oxford, UK. 30 July–7 Aug. 1935. Vol. II. Thomas Murby & Co., London. p. 37–48.
- Tanino, Y., and M.J. Blunt. 2012. Capillary trapping in sandstones and carbonates: Dependence on pore structure. *Water Resour. Res.* 48:W08525. doi:10.1029/2011WR011712
- Tian, Z., W. Gao, D. Kool, T. Ren, R. Horton, and J.L. Heitman. 2018. Approaches for estimating soil water retention curves at various bulk densities with the extended van Genuchten model. *Water Resour. Res.* 54:5584–5601. doi:10.1029/2018WR022871
- Tokunaga, T.K. 2009. Hydraulic properties of adsorbed water films in unsaturated porous media. *Water Resour. Res.* 45:W06415. doi:10.1029/2009WR007734
- van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892–898. doi:10.2136/sssaj1980.03615995004400050002x
- Verbist, K., J.M. Baetens, W.M. Cornelis, D. Gabriels, C. Torres, and G. Soto. 2009. Hydraulic conductivity as influenced by stoniness in degraded drylands of Chile. *Soil Sci. Soc. Am. J.* 73:471–484. doi:10.2136/sssaj2008.0066
- Verbist, K., W.M. Cornelis, S. Torfs, and D. Gabriels. 2013. Comparing methods to determine hydraulic conductivities on stony soils. *Soil Sci. Soc. Am. J.* 77:25–42. doi:10.2136/sssaj2012.0025
- Verbist, K., S. Torfs, W.M. Cornelis, R. Oyarzun, G. Soto, and D. Gabriels. 2010. Comparison of single- and double-ring infiltrometer methods on stony soils. *Vadose Zone J.* 9:462–475. doi:10.2136/vzj2009.0058
- Webb, P.A. 2001. Volume and density determinations for particle technologists. Micromeritics Instrument Corp., Norcross, GA.
- Weber, T.K.D., S.C. Iden, and W. Durner. 2017. Unsaturated hydraulic properties of *Sphagnum* moss and peat reveal trimodal pore-size distributions. *Water Resour. Res.* 53:415–434. doi:10.1002/2016WR019707
- Yu, A.B., J. Bridgwater, and A. Burgidge. 1997. On the modeling of the packing of fine particles. *Powder Technol.* 92:185–194. doi:10.1016/S0032-5910(97)03219-1
- Zimmerman, R.W., and G.S. Bodvarsson. 1995. The effect of rock fragments on the hydraulic properties of soils. LBL-37018. Lawrence Berkeley Lab., Berkeley, CA. doi:10.2172/102527.